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Control Strategy of Modular Multilevel DC-DC Converter Based Supercapacitor Energy Storage Systems

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ABSTRACT
In this paper, a DC-DC modular multilevel converter based supercapacitor energy storage system (MMC-SESS) is proposed to achieve peak load shifting ability for shipboard DC power grid energy storage applications. The control problems of the converter are discussed, and the current loop of the MMC-SESS is improved by combining the state of charge (SOC) balance control of the supercapacitors (SCs). In order to improve the dynamic performance of current loop, the fuzzy immune algorithm is used to replace the traditional PI controller. In SOC balance loop, the maximum SC voltage is used as the balance target, thus, the low SOC modules can regulate the sub-module operation average current according to the reference and their own SOC. In this way, since the duty cycle generated by the SOC balance loop of each submodule is negative, the system current will deviate from the given value. In order to minimize system current deviation, a current compensation loop is designed. Finally, a MATLAB/ Simulink simulation model is established to verify the proposed strategy, the results show that the current control precision and response speed are improved. In addition, the proposed strategy can also achieve SOC balancing control during charging and discharging.
***Keywords* -** Modular Multilevel Converter, Energy Storage System, Supercapacitor, State of Sharge, Fuzzy Immune.

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I. INTRODUCTION

With the development and changes of the energy structure, electric energy is replacing more and more traditional energy solutions because of its high efficiency, pollution-free and easy transmission. In the field of ship propulsion, integrated electric propulsion ships have also received extensive attention.

In integrated electric propulsion ships, there are many kinds of load forms including power propulsion load, crane and electromagnetic catapult, communication device, navigation and daily equipment, etc. Therefore, it brings great challenge to the power supply system in the integrated electric propulsion system. The composition of ship integrated power system is shown in Figure 1. Instead of connecting to the drive equipment directly, the power transmission network is powered by the advanced energy storage element. This structure provides greater power supply flexibility, efficiency, and survivability. The selection of energy storage elements is also diverse. At present, there are many excellent energy storage schemes, like battery, supercapacitor (SC) and flywheel etc. Among them, the battery has the highest energy density and is suitable for use as a medium-and-long term power source. Contrary to the battery, the SC can satisfy the requirements of fast charging and discharging with high power capacity due to its highest power density, therefore, it is widely used in the pulse load. The flywheel's energy density is not high as the SC, but it has the highest self-discharge rate, such as stop charging, its energy will run out in a few hours, and it is suitable for frequency regulation and power quality improvement in power grid [1]. In order to avoid the additional requirements on the integrated electric propulsion system caused by the pulse load in the ship, the best solution is to add a SC energy storage unit to the energy storage system to provide the pulsating power.

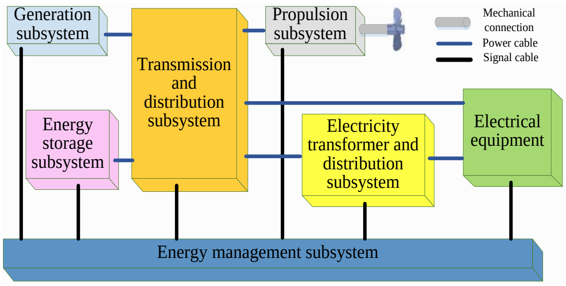

Figure 1: Composition of ship integrated power system

The single SC has low voltage and small capacity, which cannot satisfy the power capacity and voltage requirements. Therefore, it is necessary to constitute a SC module with series or parallel combination. However, the parameters of SC are very discrete and the state of charge (SOC) balance issue is a major challenge for energy storage system [2-5]. With the development of modular multilevel converter (MMC), some scholars have proposed a cascade bi-directional DC-DC converter based on MMC [2]. Because each submodule of MMC can be configured freely and flexibly, it is very suitable for the supercapacitor energy storage system, and SOC balance and power distribution control among each submodule can be achieved by modular operation. Aiming at the problem of SOC balance of energy storage structure, a flexible modulation strategy was proposed in [6], but the switching noise of capacitor voltage will be increased. In [7], an improved sorting and selection based control strategy was proposed, but the complexity of the system is increased obviously, and the step loss or jump phenomenon will occur if the step size selection is not reasonable. Several converter schemes were propoed for high voltage and high power energy storage application [8-9], and the conclusion is that the modular multilevel energy storage topology has an obvious advantage in high voltage and high power bidirectional power conversion application.

In this paper, the closed-loop control structure of voltage and current is designed for the MMC-SESS. Meanwhile, in order to solve the problem that the traditional PI controller has poor dynamic performance, the fuzzy immune PI control is adopted to improve the adaptability of the current loop. At the same time, the SOC balance control is carried out, so that the system can realize the SOC balance of the SCs while stabilizing the output current. Finally, the effectiveness of the proposed control method is verified by simulation results.

II. BASIC STRUCTURE OF MMC-SESS

The topological circuit of MMC-SESS is shown in Figure 2, and N sub-modules is concocted in series to meet the variation voltage applications. And each sub-module consists of switching devices (S_{i1}, S_{i2} and $i \in \{1,2,\ldots,N\}$), supercapacitor, filter inductor and capacitor. L is system inductor, R_L is the equivalent resistance of system inductor. According to the different work status of the switching devices, the converter can operate in two different modes including energy conversion mode and bypass mode, which is shown in Figure 3.

In order to reduce the output voltage and current ripple, as show in Figure 4, the carrier phase-shifting PWM(CPS-PWM) method is adopted, the phase-shifting angle of each sub-module is $2\pi/N$. Through the above analysis, the basic equation of the converter can be obtained as:

$$\begin{cases} u_{dc} = \sum_{i=1}^{N} u_{SCi} d_i - (L\dfrac{di_L}{dt} + i_L * R_L) \\ i_{SCi} = d_i * i_L \end{cases} \qquad (1)$$

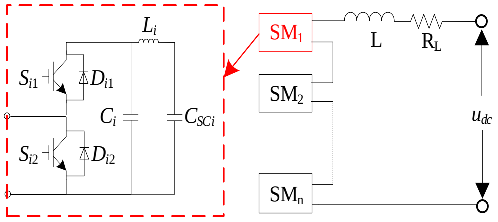

Figure 2: Topological circuit of MMC-SESS

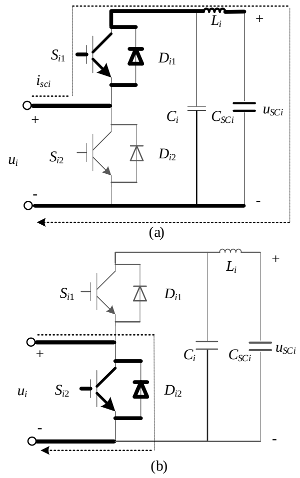

Figure 3: Operation modes. (a) energy conversion mode (b) bypass mode

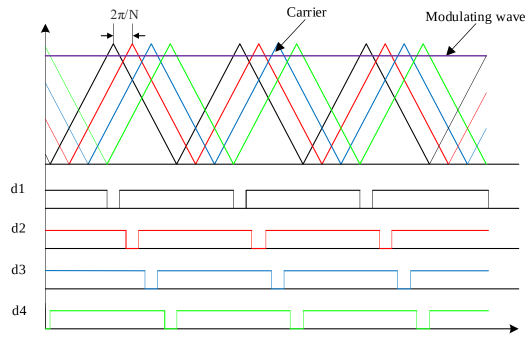

Figure 4: Schematic diagram of CPS-PWM

In (1), u_{dc} is the output voltage of the converter, u_{sci} is the voltage of each SC, d_i is the duty cycle of S_{i1}, i_L is the output current of dc bus, i_{Sci} is the current flowing in or out of each energy storage sub-module.

The SOC is used to describe the residual charge capacity of energy storage equipment. By definition, the SOC can be obtained easily.

$$SOC_i = \frac{Q_i}{Q_{Ni}} = \frac{Q_{0i} - \Delta Q_i}{Q_{Ni}} = \frac{Q_{0i} - \int_0^{\tau} i_{SCi}\,dt}{Q_{Ni}} \qquad (2)$$

Where Q_{0i} is the initial charge value of the sub-module, ΔQ_i is the released or absorbed charge capability of the sub-module in one switching cycle, Q_{Ni} is the rated charge capability of the SC.

In practice, SOC cannot be measured directly, so it needs to be estimated. In this paper, open circuit voltage and ampere-hour metering are combined to calculate the SOC. Firstly, the initial state of the SC is determined by its open circuit voltage. Then the ampere-hour method is used to calculate the remaining power of SC. Due to the accumulation of interference errors caused by charge-discharge efficiency, temperature and other factors during ampere-hour measurement, it is necessary to make corresponding corrections. The SOC can be expressed as:

$$SOC_i = a\left(\frac{U_{oci}}{U_{Ni}}\right)^2 + b\left(\frac{U_{oci}}{U_{Ni}}\right) \tag{3}$$

Where, U_{OCi} and U_{Ni} are open circuit voltage and rated voltage of the SC respectively, and a and b are the correction coefficients obtained by linear fitting.

According to (2), the SOC of each SC can be adjusted by the duty ratio of its sub-module when the bus current is stable.

III. CONTROL STRATEGY

The MMC-SESS is a conversion system with one end series and one end independent, and the charging and discharging of the energy storage system is regulated by controlling the current of the inductor *L*. In order to realize the stable operation of the system, the converter control consider needs to contain two control loops, one is the current closed loop that controls the inductor current, and the other is the SOC balanced loop that realizes the balanced operation of the SC. These two closed loops are all achieved by adjusting the duty cycle of the sub-module.

Therefore, in this paper, the control objectives can be summarized as the following two points: (1) stable DC bus current; (2) realize the SOC balance of each sub-module.

The overall control block diagram of the system is shown in Figure 5, and it is composed by three parts including current loop, SOC balance loop and current compensation loop.

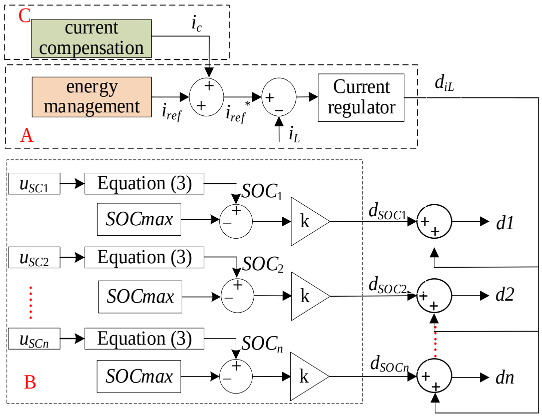

Figure 5: Overall control structure

3.1 Current Loop Design

In the control system of this paper, the current loop is a first-order system, and the current can be controlled by PI regulation theoretically. The dynamic performance of the control system is highly required due to the different number of sub-modules are constantly switched on and off and the discreteness of each SC during the regulation process. Therefore, a fuzzy immune PI control method is proposed in this paper, and this control method is based on the two-dimensional formula [10]. The fuzzy immune PI structure is shown in Figure 6. It can adapt to the requirements of the controller intelligently and improve the dynamic performance of the system significantly.

In the immune algorithm, the error $e(k)$ at time k is regarded as the number of the k generation antigen, and the error difference between time k and time k-1 is regarded as the change, so the output at time k can be obtained as:

$$y(k) = K\left\{1 - \eta f\left[y(k-1), \Delta y(k-1)\right]\right\} e(k) \tag{4}$$

In the immune algorithm $f[y(k\text{-}1), \Delta y(k\text{-}1)]$ is set by the fuzzy algorithm. and the $y(k$-1) is E, $\Delta y(k$-1) is EC, and output $f(E, EC)$ is U. The fuzzy interval is defined as: P, N and Z, and make the following four vague rules:

If E is P and EC is P, then U is N;
If E is P and EC is N, then U is Z;
If E is N and EC is P, then U is Z;
If E is N and EC is N, then U is P.

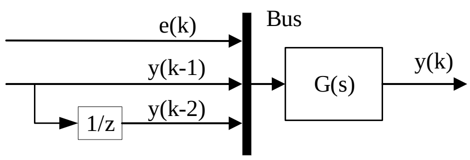

Figure 6: Fuzzy immune PI structure

$$\begin{cases} P(k) = K_p(1-\eta_p U) \\ I(k) = K_I(1-\eta_I U) \end{cases} \quad (5)$$

K_P, K_I and η_P, η_I are promoting factors and inhibitors of proportional and integral coefficients respectively. Finally, the output of this loop is:

$$d_{iL} = y(k) = y(k-1) + I(k) e(k) + P(k)(e(k) - e(k-1)) \quad (6)$$

3.2 SOC Balance Loop Design

The purpose of the SOC balance loop is to fully exploit the potential and life of the energy storage device. Meanwhile in order to make the output current ripple of multilevel converter is small enough, the current should be controlled independently under the condition that SOC of each sub-module is equal. Therefore, the SOC balance loop is very necessary for the system proposed in this paper.

Therefore, in order to balance the SOC, the duty ratio of each sub-module needs to be adjusted according to the charge and discharge of the system in the control process. More specifically, in the discharge process, sub-modules with large SOC values discharge more, and sub-modules with low SOC values discharge less, and vice versa. It can be known from [2] that the control target can be achieved by proportional regulator. The control of this loop is shown in part B of Fig 5. In this paper, the maximum value of SOC is adopted as the balance target for each sub-module, which avoids the average calculation compared with the traditional balance method and can improve the operation speed of the controller. Therefore, the duty ratio output of this loop can be expressed as:

$$d_{SOCi} = k * (SOC_i - SOC_{max}) \quad (7)$$

In (7), k is the proportional coefficient of SOC balance loop and it is greater than zero.

3.3 Current compensation strategy

According to (7), it can be known that $\sum d_{SOCi}<0$, therefore, the following relationship can be obtained.

$$(d_{iL} + \sum d_{SOCi}) < d_{iL} \quad (8)$$

The above equation shows that the duty ratio signal of SOC balance loop will affect the current control loop and make the current deviate from the given value. In addition, the voltage drop generated by the switching devices will also affect the current control loop, therefore, in order to eliminate those effects, and improve the system current regulation performance, a current compensation strategy is proposed, which is shown in Part C of Figure 5.

Assume that the current compensation value is λ, according to different stages of charge and discharge, the compensation value in this paper can be calculated as:

$$\begin{cases} \lambda = sign(i_L)(i_{ref} - i_L) & |i_{ref}| > |i_L| \\ \lambda = 0 & |i_{ref}| < |i_L| \end{cases} \quad (9)$$

Therefore, the final duty ratio of each sub-module can be obtained from the above loops.

$$d_i = G_i(s)[(i_{ref} + \lambda) - i_L] + k(u_{SCi}) \quad (10)$$

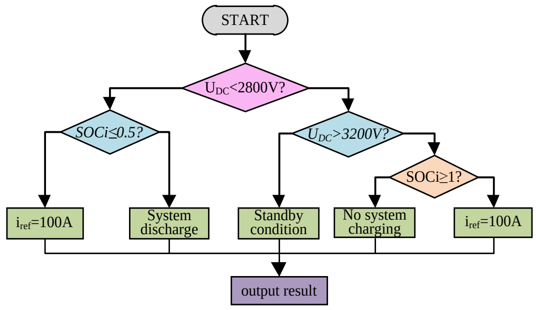

Figure 7: Energy management strategy

IV. ENERGY MANAGEMENT STRATEGY

In this paper, when the bus voltage fluctuates, it requires the energy storage device can operate instantly, and absorb or release energy to dc bus. At the same time, in order to make the SC to get better conditions of use and the service life, overuse of it should be avoided. In the charging process, its maximum SOC value should be about 1, and in the discharging process, the lowest value should be about 0.3. In this way, the health and stability of the whole system can be guaranteed, and the energy management strategy is shown in Figure 7.

V. SIMULATION ANALYSIS

The proposed control strategy for MMC-SESS system has been developed in Matlab/Simulink. The simulation parameters are shown in Table 1.

In order to verify the validity of the current compensation strategy, the traditional PI controller is used to simulate two different control systems with compensation and non-compensation respectively. The results are shown in Figure 8.

Table 1: Simulation parameter

Item	Value
Number of sub - modules	8
Switching frequency	2.5kHz
Arm inductance	2.5mH
DC capacitance	1000μF
Filter capacitance submodule	4700μF
Filter inductance	47μH
Voltage rating of SC	16.2V

Capacitance rating of SC	58.33F
Module 1 initial voltage value	15V
Module 2 initial voltage value	15.6V
Module 3 initial voltage value	15.2V
Module 4 initial voltage value	14.9V
Module 5 initial voltage value	15.8V
Module 6 initial voltage value	14.5V
Module 7 initial voltage value	15.8V
Module 8 initial voltage value	16V

The PI parameters used in the non-compensated system are respectively 100 and 10. The PI parameters and compensating coefficients used in the compensated system are respectively 10, 2, 5. It can be seen from the figure that the current shown in the red box has dropped. It emerges because the sub-module acts when the voltage balance control reaches a certain range. That will affect the current control. Through the control results can be seen that the current drop can be compensated by current compensation loop.

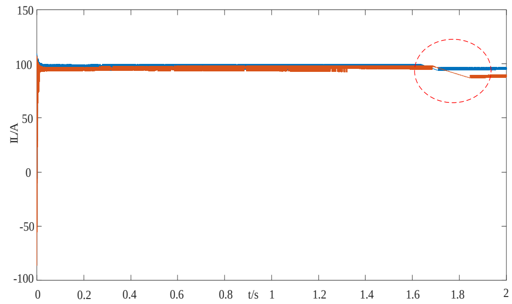

Figure 8: Comparison of the current performance with and without compensation

The bus current and sub-module SOC balanced simulation waveforms under the traditional PI controller and the proposed control strategy are shown in Figure 9 and 10, respectively. By comparing the two figures, it can be see that the proposed control strategy has better dynamic performance and lower current ripple. The proposed control strategy can make the bus current reach the given value more quickly, even if the current has drop, it can be back to given value by itself quickly. At the same time, sub-module SOC can achieve balance actively.

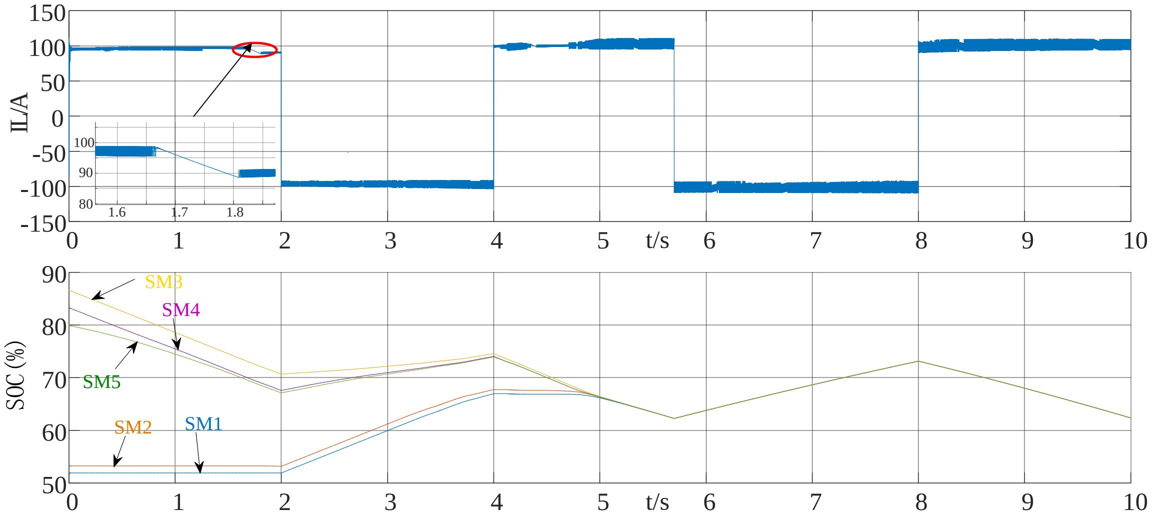

Figure 9: Waveforms of bus current and SOC balance based on the traditional PI controller

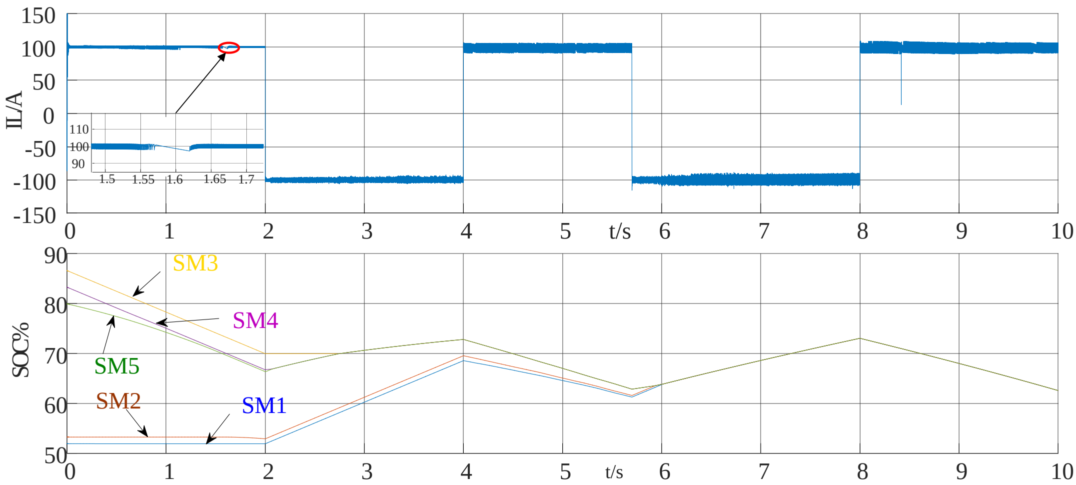

Figure 10: Waveforms of bus current and SOC balance based on the proposed control strategy

VI. CONCLUSIONS

In this paper, we mainly studied the control strategy of the modular multilevel supercapacitor energy storage system in the background of ship energy storage system. In this system the fuzzy immune PI algorithm is used. At the same time a current compensation strategy and a maximum voltage tracking method is proposed based on the practical application conditions. Meanwhile, a maximum voltage tracking method is proposed. Finally, combined with energy management strategy, effectiveness of the proposed control method is verified by MATLAB/Simulink simulation tools. For the ship energy storage system, it has a certain application value. We will continue to improve the algorithm and control strategy to achieve better dynamic performance.

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